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PRE-PROGRAMMABLE OPTICAL FILTERING / AMPLIFYING METHOD AND APPARATUS

BACKGROUND OF THE INVENTION

Field of the Invention

[0001] This invention relates generally to the field of optical communications and in particular to wavelength division multiplexed (WDM) fiber optic communications, where multiple independent optical signals are carried on the same single mode optical fiber for long distance transmission. More specifically, it pertains to dynamic spectral filtering of WDM signals used to maintain the desired relative intensities of the multiple signals as they are carried through an optical communications network, and to the gain-flattening filters used to provide optical amplifiers with uniform spectral response.

Description of the Prior Art

[0002] Nonuniform signal power levels in WDM communication systems can lead to transmission errors, especially when a signal is transmitted through a chain of optical amplifiers. Optical amplifiers are designed to have a gain that is approximately constant as a function of wavelength, provided the average input power is within specified limits. The gain spectrum of erbium-doped fiber is not intrinsically flat. Typically, static gain-flattening filters (GFFs) are used to flatten the gain spectrum in erbium-doped fiber amplifiers (EDFAs) for a particular average erbium inversion level and erbium-doped fiber length.

[0003] The change in gain shape $\delta G(\lambda)$(in dB) with total power-gain change ΔG (in dB) is given by:

[0004] $$\delta G(\lambda) = g(\lambda)\Delta G,$$

[0005] where $g(\lambda)$ is the tilt function. An amplifier with GFF having a flat gain profile (A) for a particular total power gain setting is shown in Figure 1. As can be seen with reference to that Figure, as the gain setting is changed, the gain profile tilts, favoring shorter (B) or longer wavelengths (C), as the total power gain is decreased or increased, respectively, and changes shape, developing broad spectral features. In order to maintain an approximately flat gain spectrum for different net amplifier gains, a variable optical attenuator (VOA) is typically inserted between two stages of the amplifier, as in Figure 2. Increasing the VOA loss reduces the net amplifier gain while the erbium inversion level, and hence, gain shape, remains constant.

[0006] Unfortunately, as the VOA loss increases (the amplifier gain decreases), the noise figure (NF) of the amplifier degrades. This degradation is especially severe if other loss elements, such as the GFF or a dispersion compensation module (DCM), are included at the same midstage. Moreover, NF degradation is particularly acute in EDFAs that must satisfy high dynamic-range requirements. Increasing the number of gain stages and minimizing the loss between any two stages reduces the NF impact. Also, a single VOA can also be replaced by two VOAs and an additional intervening gain stage. These measures increase cost, complexity, and power consumption, however.

[0007] An alternative solution to the VOA and static GFF combination is a dynamic or tunable gain equalizing filter that can produce the transfer functions required to equalize the optical amplifier gain over the required range of gain settings.

[0010] Figure 3 shows a specific example of such a prior art SSP filter **300**, a dynamic gain equalizer (DGE), designed to provide arbitrary attenuation on each channel of a multi-wavelength signal for dynamic spectral power equalization. The basic concept of the DGE is disclosed in United States Patent No. 5,745,271, “Attenuation device for wavelength multiplexed optical fiber communications”, and

the physical configuration shown is disclosed in US Patent No. 6,307,657, “Optomechanical platform”. Optical input signals are directed by input fiber **301** through an optical circulator **302** and enter the free-space optical system through input/output fiber **303**. Light emitted from input/output fiber **303** is collimated by a first pass through lens 404 to illuminate a reflective diffraction grating **305**. The diffraction angle is proportional to the wavelength, so grating **305** acts to separate each wavelength signal by angle. A second pass through lens **304** to a spectrally dispersed plane **306** focuses the diffracted signals where each signal is vertically displaced according to the wavelength.

[0011] A micromechanical attenuation device **307** located at the spectrally dispersed plane consists of a column of individually controllable optical attenuators **308**. Light which is reflected from the attenuator array retraces the input path as it is recollimated by a third pass through lens **304**, diffracting again from grating **305**, and finally focused back into the input/output fiber **303**. For clarity, the arrows drawn in Figure 4 indicate the first pass of the light through the optical system from input/output fiber **303** to attenuator array **308**. On the return path from attenuator array **308** to input/output fiber **303** the direction is reversed.

[0012] Attenuation device **307** may be designed so that each attenuator **308** absorbs a controlled portion of each wavelength signal, as described in US Patent number 6,307,657. Other types of attenuation devices can also controllably reduce the amount of light that is coupled into the single mode output fiber **303**. Figure 3 depicts an attenuator device **307** that contains a linear array of tilting micro-mirrors **308** controlled by external electrical connections **309**. When one micro-mirror is tilted, the corresponding wavelength signal imaged in a second pass through the optical system is incident on input/output fiber **303** at a controlled angle relative to the fiber face. The efficiency of coupling into the fiber depends on angle of incidence, so a controlled tilt of the micro-mirror controllable reduces the output power of the corresponding wavelength signal coupled back into the input/output fiber **303**. Finally, the backwards-propagating output signals pass through the

optical circulator **302** and are directed into a separate output fiber **310**. Fiber optic components based on variations of this design are commercially available as, for examples, the Dynamic Channel Equalizer sold by LightConnect, Inc., and the "AgileWave" (TM) Dynamic Spectral Equalizer sold by Cidra, Inc. In additon, DGEs may be based on radically different architectures, such as a concatenation of interferometers with dissimilar free-spectral ranges.

[0013] Ideally, DGEs generate a loss function with nearly arbitrary shape, limited by their dynamic range and spectral resolution. In addition to amplifier gain flattening, DGEs can correct imbalances in the input spectrum that have accumulated in the preceding network. However, DGE control generally requires measurement of the amplifier output spectrum. The DGE is operated in a closed loop with feedback from a spectrum analyzer. Several iterations may be required for the output spectrum to converge to the desired shape. Feedback can also be used to adjust the DGE in response to long-term drift or variations over temperature. Open-loop operation may also be possible, saving the cost of the spectrum analyzer, for certain types of DGEs, if a sufficiently simple and accurate device model is applicable. However, extensive calibration of the DGE over temperature will still be required.

[0014] A DGE should tune from one filter shape to another in such a way that the loss at every wavelength changes monotonically. This property is difficult to achieve in general for certain DGE technologies such as harmonic equalizers, which are based on a series of interferometers, and acousto-optic equalizers, which employ acoustical vibrations to couple light within a certain optical band out of the guided mode of a fiber.

[0015] In addition to the added control difficulties, DGEs generally are more costly and add more excess loss than the GFF/VOA combination they would replace. The extra cost comes from the many degrees of freedom required in the DGE and its relatively high spectral resolution. These characteristics allow the

DGE to correct accumulated ripple in a system, which may be of nearly arbitrary shape. However, in typical systems with gain-flattened EDFAs, the ripple need not be corrected every span. For a dynamic filter to just flatten EDFA gain, without correcting accumulated ripple, only one degree of freedom is required. As the gain changes, the filter need only tune from one preset filter shape to another. Also, the filter resolution need not exceed the resolution of the amplifier gain shape.

[0016] Even a low-resolution DGE requires many degrees of freedom to produce a smooth shape that closely matches the erbium gain shape. The DGE **300** uses bulk optics and a diffraction grating to disperse light onto a discrete array of attenuating elements. The pitch of these elements must be smaller than the monochromatic spot size or else residual ripples will appear in the filter shape. Many attenuators are also required since their registration cannot be pre-aligned to the minima and maxima of the required GFF shapes. The array of attenuators, whether they are MEMS or liquid-crystal devices, has a minimum practical pitch which is on the order of, or larger than, the fiber mode diameter. Thus, these DGEs typically increase the spot size by designing an imaging system with magnification greater than one, resulting in unfolded optical designs with long optical path lengths. Compared to components with shorter folded geometries, these designs are bulkier with more components and higher insertion loss, and it is more difficult and expensive to make such devices insensitive to temperature variations.

[0017] Although it would be desirable to provide the functionality of a full-featured DGE and associated spectral monitoring and feedback control in each optical amplifier, the total cost of such a solution is unacceptable in terms of expense, complexity, power dissipation, and physical volume. A need therefore exists for a simple pre-programmable gain equalization filter that is capable of providing a limited number of pre-determined spectral filter functions for a fraction of the cost of a full DGE.

SUMMARY OF THE INVENTION

[0018] We have developed a new method and associated apparatus for dynamic spectral filtering of multi-wavelength fiber optic signals, as used in optical amplification, security or other applications, wherein a set of spectral filter patterns are pre-recorded as a 2-dimensional optical filter with a spatially varying pattern of phase, absorption, or reflectivity. A multi-wavelength input signal carried on an optical fiber is spectrally dispersed using bulk diffractive and imaging optics to illuminate a linear region of the filter, which acts as a spectral variable attenuator by preventing a predetermined portion of the signal from being collected into an optical fiber output.

[0019] In prior art dynamic spectral filters, an array of active devices are located at the spectrally dispersed plane. Individual electrical control of the array of devices allows arbitrary attenuation profiles to be imposed upon the multi-wavelength optical signal. However, such general-purpose dynamic spectral equalizers require optical systems that maintain precise alignment to high-resolution modulator arrays, as well as the multi-channel monitoring and feedback control.

[0020] According to the present invention, the prior art technique of using a linear array of active modulators is replaced with a static 2-dimensional optical filter, which is in effect a stack of predetermined linear modulation patterns. Instead of changing a single linear filter, the spectrally dispersed signal is steered onto the linear area of the 2-dimensional filter to select one of the pre-recorded patterns. Beam steering of the spectrum may be advantageously accomplished using a single actuator.

[0021] In a preferred embodiment, the control is accomplished by tilting a diffraction grating or fold mirror. Tilt in one axis selects which of the linear pre-

recorded filters is illuminated. Optional tilt in the orthogonal axis controls the center wavelength of the pre-recorded filter function.

[0022] The position of the dispersed spectrum can be monitored by monitoring the position of the single actuator, or through an optical detector located proximate to the spectral filter to directly monitor the position of the dispersed spectrum relative to the filter. The resulting programmable spectral filter is substantially smaller, simpler, and less expensive than prior art dynamic gain equalizers.

BRIEF DESCRIPTION OF THE DRAWING

[0023] **Figure 1** is a graph showing the gain v. wavelength for an amplifier with gain flattening filters;

[0024] **Figure 2** shows a prior art filter having a variable optical attenuator inserted between the two stages of the amplifier;

[0025] **Figure 3** shows a prior art, switched spectral-plane filter;

[0026] **Figure 4** shows an illustrative fiber-optic communications link in an optical communications network according to the present invention;

[0027] **Figure 5** shows an illustrative optical amplifier;

[0028] **Figure 6** shows an optical system of Figure 3, modified according to the present invention;

[0029] **Figure 7(a)-7(c)** shows the effect of laterally shifting spectrum;

[0030] **Figure 8** is a graph showing the loss v. wavelength for different filter shapes;

[0031] **Figur 9** shows a double-pass spectral filter having an input through a second fiber;

[0032] **Figure 10** shows a spectral filter having a roof prism;

[0033] **Figure 11(a) – 11(d)** shows configurations for steering a spectrally dispersed beam;

[0034] **Figure 12** shows an optical filter including a spectrum steering system using lateral actuation of the patterned filter;

[0035] **Figure 13** shows a position sensitive detector located beneath a spectral filter;

[0036] **Figure 14** shows a optical sensing arrangement utilizing photodetectors;

[0037] **Figure 15** shows the optical sensing arrangement of Figure 14, having an additional shield; and

[0038] **Figure 16** shows the bands of high and low transmisson or reflectivity between filter stripes.

DETAILED DESCRIPTION OF THE INVENTION

[0039] An illustrative fiber-optic communications link in an optical communications network in accordance with the present invention is shown in **Figure 4**. As can be readily appreciated by those skilled in the art, a transmitter may transmit information to a receiver over a series of fiber links. Each fiber link may include a span **16** of optical transmission fiber. Fiber spans **16** may be on the order of 40-160 km in length for long-haul networks or may be any other suitable length for use in signal transmission in an optical communications network. Link **10** may be a point-to-point link, part of a fiber ring network, or part of any other suitable network or system known in the art.

[0040] With continued reference to **Figure 4**, the communications link shown therein may be used to support wavelength division multiplexing arrangements in which multiple communications channels are provided using multiple wavelengths of light. For example, the link shown in **Figure 4** may support a system with 40 channels, each using a different optical carrier wavelength. Optical channels may be modulated at, for example, approximately 10 Gbps (OC-192). The carrier wavelengths that are used may be in the vicinity of 1527-1605 nm. These are merely illustrative system characteristics. If desired, fewer channels may be provided (e.g., one channel), more channels may be provided (e.g., hundreds of channels), signals may be carried on multiple wavelengths, signals may be modulated at slower or faster data rates (e.g., at approximately 2.5 Gbps for OC-48 or at approximately 40 Gbps for OC-768), and different carrier wavelengths may be supported (e.g., individual wavelengths or sets of wavelengths in the range of 1240-1670 nm).

[0041] Of course, optical amplifiers **18** may be used to amplify optical signals on link **10**. Optical amplifiers **18** may include booster amplifiers, in-line amplifiers, and preamplifiers. Optical amplifiers **18** may be rare-earth-doped fiber amplifiers such as erbium-doped fiber amplifiers, amplifiers that include discrete Raman-pumped coils, amplifiers that include pumps for optically pumping spans of transmission fiber 16 to create optical gain through stimulated Raman scattering, semiconductor optical amplifiers, or any other suitable optical amplifiers.

[0042] Link **10** may include optical network equipment such as transmitter **12**, receiver **14**, and amplifiers **18** and other optical network equipment **20** such as dispersion compensation modules, dynamic filter modules, add/drop multiplexers, optical channel monitor modules, Raman pump modules, optical switches, etc. For clarity, aspects of the present invention will be described primarily in the context of optical network equipment **20** having gain stages and spectral control

capabilities. This is, however, merely illustrative. The features of the present invention may be used for any suitable optical network equipment if desired.

[0043] Computer equipment **22** may be used to implement a network management system of which a variety are known and used. Computer equipment such as computer equipment **22** may include one or more computers or controllers and may be located at network nodes and one or more network management facilities. As indicated by lines **24**, the network management system may communicate with optical amplifiers **18**, transmitter **12**, receiver **14** and other optical network equipment **20** using suitable communications paths. The communications paths may be based on any suitable optical or electrical paths. For example, communications paths **24** may include service or telemetry channel paths implemented using spans **16**, may include wired or wireless communications paths, may involve communications paths formed by slowly modulating the normal data channels on link **10** at small modulation depths, etc. Paths **24** may also be used for direct communications between amplifiers 18 and other optical network equipment.

[0044] Additionally, computer equipment **22** may be used to gather spectral and/or aggregate power information from transmitter **12** (e.g., an output power spectrum), receiver **14** (e.g., a received power spectrum), and amplifiers **18** and other equipment **20** (e.g., input and output power spectra and gain spectra).

[0045] Finally, computer equipment **22** may use the gathered information from this equipment or other suitable equipment in the network to determine how the operating conditions of amplifiers **18** and the other equipment in link **10** are to be controlled. Operating conditions include the gain and output-power settings of optical amplifiers and the transfer functions of controllable spectral filters. Computer equipment **22** may issue commands to amplifiers **18**, transmitters **12**, receivers **14**, and other equipment **20** that direct this equipment to make appropriate adjustments. The adjustments may be used to optimize the gain or

signal spectrum flatness along link **10**, may be used to optimize the end-to-end or node-to-node signal-to-noise ratio across the signal band or spectrum, or may be used to implement any other suitable control or optimization functions for link **10**.

[0046] An illustrative optical amplifier **18** is shown in **Figure 5**. With reference now to that **Figure 5**, optical input signals may be provided to input fiber **26**. The optical input signals may be, for example, data traffic being carried on the wavelength-division-multiplexing channels in the signal band of link **10** that is provided to input fiber **26** over a span of fiber **16**. Gain stages **30** may be used to provide optical gain for the optical signals. Corresponding amplified output signals may be provided at output fiber **28**.

[0047] As can be appreciated, programmable spectral filter **32** may be used to modify the gain and output power spectra of amplifier **18**. Programmable spectral filter **32** may be referred to as a tunable gain-flattening filter, because programmable spectral filter **32** may be used alone or in combination with a static spectral filter to flatten the gain spectrum of amplifier **18**.

[0048] In the prior art, and while not specifically shown in this **Figure 5**, a dynamic gain equalizer (DGE) would be used in place of programmable spectral filter **32**. A DGE has multiple degrees of freedom that can be controlled to approximate almost any filter shape, subject to the limits of the DGE dynamic range and spectral resolution.

[0049] In sharp contrast to the prior art, instead of using a general purpose DGE, we now teach the use of a novel inexpensive pre-programmable spectral filter **32** that contains a set of predefined filter shapes. Such a filter can be used in EDFAs to replace the GFF and VOA with a tunable gain-flattening filter (TGFF), providing much of the advantage of a general purpose DGE at a fraction of the cost. An applied electrical signal results in switching or tuning from one filter to another.

[0050] For the gain equalization application, the required filter shape can be described as a two-dimensional function of wavelength and amplifier gain. This 2-D function can be recorded as a variable reflectivity on a planar surface. Using such a filter, the TGFF can smoothly transition from one filter shape to another and equalize the amplifier at any arbitrary gain setting. The TGFF has one degree of freedom that is used to tune from one filter shape to another and may also include another degree of freedom that allows the wavelength registration of the filter set to be shifted.

[0051] The TGFF uses an optical design similar to many DGEs in that it uses a diffraction grating to disperse the spectrum and an imaging system to image the spectrum onto a surface of variable reflectivity or loss. Reflected light from this surface is remultiplexed by the grating and focused into an output fiber. However, the TGFF utilizes a series of smoothly varying reflection profiles rather than the array of discrete elements of variable reflectivity found in DGEs. Thus, a shorter folded geometry with unity magnification is suitable, resulting in significant cost savings.

[0052] In general, various additional components may be positioned at locations along the main fiber path through an amplifier **18**. These components may include isolators, taps and photodetectors for optical monitoring (e.g., to measure the gain of amplifier **18**), filters (e.g., static spectral filters), wavelength-division-multiplexing couplers, attenuators, dispersion-compensating elements such as dispersion-compensating fiber, gain stages, pumps, pump couplers, optical channel monitors, optical switches, etc. The operation of the components and gain stages **30** and programmable spectral filter **32** may be controlled using control unit **34**.

[0053] Control unit **34** depicted in **Figur 5** advantageously may be based on any suitable control circuitry and may include one or more microprocessors,

microcontrollers, digital signal processors, field-programmable gate arrays or other programmable logic devices, application-specific integrated circuits, digital-to-analog converters, analog-to-digital converters, analog control circuits, or memory devices, etc known to the art. Control unit **34** may include communications circuitry that supports the communications between control unit **34** and computer equipment such as computer equipment **22** of **Figure 5** or other equipment in the network.

[0054] Amplifier **18** may be based on an optical network card and may use the communications circuitry to communicate with a controller mounted in a rack in which the card is mounted. The controller may be part of computer equipment **22** or may communicate with computer equipment **22**. If desired, amplifier **18** may be implemented as a module that is part of an optical network card. The module may use the communications circuitry in unit **34** to communicate with a controller or other computer equipment **22** or to communicate with additional communications circuitry on the card that in turn supports communications with a controller or other computer equipment **22** in the network. These are merely illustrative communications arrangements that may be used to allow amplifier **18** to communicate with the equipment in the network. Any suitable arrangement may be used if desired.

[0055] Amplifier **18** may have taps and optical monitors for tapping a fraction (e.g., 2%) of the light propagating through amplifier **18**. The optical monitors may be based on photodetectors or any other suitable optical monitoring arrangement. Transimpedance amplifiers in the monitors or in control unit **34** may be used to convert current signals from the photodetectors in the monitors into voltage signals for processing by analog-to-digital converters or other suitable processing circuitry. The processing circuitry may be located in the monitors or in control unit **34**.

[0056] Control unit **34** may use input and output power measurements from taps and monitors in amplifier **18** to measure the gain of individual gain stages **30**

or aggregates of gain stages **30**. These gain measurements may be used in suppressing gain transients. Such gain transients may arise from sudden changes in the number of channels present on link **10** (e.g., due to a network reconfiguration or an accidental fiber cut). When signal and gain fluctuations are detected using the taps and monitors (e.g., input and output taps and monitors associated with each stage), control unit **34** may control the power of the pump light produced by the pumps in gain stages **30** to ensure that the gain or output power of the stages and amplifier **18** remains constant.

[0057] With further reference to the amplifier arrangement depicted in **Figure 5**, the gain spectrum of amplifier **18** may be controlled by using control unit **34** to adjust programmable spectral filter **32** and the gain of the gain elements (e.g., the optically-pumped fiber) in the gain stages of amplifier **18**. If programmable spectral filter **32** is provided as part of a stand-alone programmable spectral filter module or other equipment without gain stages, control unit **34** may be used to adjust programmable spectral filter **32** to produce a desired loss spectrum. For clarity, the present invention will be discussed primarily in the context of equipment that includes one or more gain stages. This is, however, merely illustrative.

[0058] By way of additional background, the gain shape of many optical amplifiers $G(\lambda)$ can be determined from a measurement of its total power gain G_{tot} alone, $G(\lambda)=g(\lambda,G_{tot})$. Such amplifiers include semiconductor optical amplifiers (SOAs), Raman amplifiers, rare-earth-doped amplifiers, such as EDFAs, and parametric amplifiers operated at power levels where the gain is unsaturated. Such amplifiers also include amplifiers operating in gain saturation if the communication signals amplified are modulated at speeds significantly in excess of the amplifier gain-relaxation time, as is the case with EDFAs in fiber optic communication systems. Amplifier-gain-stage input and output powers, measured by optical power monitors, may be used as feedback to control the amplifier gain

and output power while adjusting the programmable spectral filter to keep the gain spectrum of amplifier **18** flat, or at some other desirable gain shape.

[0059] The spectral filter may be designed to keep the gain shape constant as the gain varies. In particular, the filter shape $f(\lambda, a)$ depends on a control parameter a which can be related to G_{tot} by the control unit such that

[0060] $$\frac{\partial}{\partial G_{tot}}\left(g(\lambda, G_{tot}) \cdot f(\lambda, a(G_{tot}))\right) = 0$$

[0061] If the amplifier is operated in a constant-gain mode, the programmable spectral filter will be kept at a constant nominal setting. Monitors internal to the programmable spectral filter may provide feedback to the control unit to maintain the filter at a constant setting. The filter may include a temperature sensor, and the control unit may adjust the filter setting so as to keep the spectral filter shape constant over changes in temperature. This compensation may include adjustment of the wavelength registration of the filter.

[0062] As the amplifier input power changes, the control unit **34** will adjust gain stages **30** so as to keep the gain constant. Such adjustments might include changing the output power of diode pump lasers pumping erbium-doped fiber in the gain stages or might include changing the attenuation of variable optical attenuators. These changes may occur on a sufficiently fast time scale so as to suppress undesirable optical transients, or they may occur on a slower time scale.

[0063] When the amplifier is operated in constant gain mode the programmable spectral filter will only be adjusted when the control unit **34** receives instruction to change the amplifier gain. These instructions may be transmitted through computer equipment **22** and over communication links **24** or over any other suitable communication link. The amplifier gain and programmable spectral filter setting are optimally adjusted synchronously so that the gain shape is held

constant. Optical power monitor readings can be used to monitor the gain and provide feedback during the adjustment. Also, the programmable spectral filter may include internal monitors of its actual spectral setting. These internal monitors may also be used as feedback to the control unit during the adjustment.

[0064] The amplifier may be operated in non-constant-gain modes such as constant-output-power mode for which the gain is not kept constant as the input power changes. In these cases, measured changes in amplifier gain will be used to determine how the spectral filter should be adjusted so as to keep the desired gain shape. Advantagiously, the filter may be adjusted synchronously with changes in input power so that the gain shape is always constant. Otherwise, the filter may be adjustment may lag input power changes, eventually returning the amplifier gain to the correct shape.

[0065] Spectral filter adjustments may also be used to change the gain shape. For example the spectral filter may be designed to introduce a controllable linear tilt to the gain shape. Such a tilt may be used to compensate for Raman induced tilt in the WDM signal spectrum.

[0066] The optical channel power spectrum may be measured at various points in the link. An optical channel monitor could be included within amplifier **18** or external to it in link **10** (**Figure 5**). If an external optical channel monitor or other spectrum analyzer is used to gather spectral information for an amplifier **18**, the spectral information may be provided to the control unit **34** in that amplifier **18** through computer equipment **22** and over communication links **24** or over any other suitable communications link. This spectral information can be used to optimize the setting of the spectral filter. However, an advantage of the disclosed spectral filter over DGEs is that feedback from an optical channel monitor is not essential to good control.

[0067] Besides the gain flattening application, the programmable spectral filter could be used for other applications such as producing a band of filtered ASE of adjustable width and center wavelength.

[0068] The programmable spectral filter relies on the principle of spectral steering. The dispersed signal spectrum is imaged onto a two-dimensional surface of variable reflectivity, which serves as a filter. Translating the imaged spectrum in one or two dimensions across the filter's surface varies the spectral shape of the filter.

[0069] With reference now to **Figure 6**, there is shown the basic concept of the invention, and in particular an optical system **600**. Specifically, multiple wavelength optical input signals are carried on optical fiber **601** through optical circulator **602** to input/output fiber **603**. Light emitted into a free-space volume by input/output fiber **603** is collimated by lens **604** and illuminates a reflective diffraction grating **605** which is mounted on a tip/tilt stage **606** capable of controllably rotating grating **605** about the Y-axis through electrical connections **607**. Optionally, grating **605** may rotate about the X-axis, as well, with control though electrical connections **607**. Each wavelength signal is diffracted by grating **605** into a distinct angle corresponding to its wavelength; for illustration, two wavelength signals **611** and **612** are drawn using a dashed and dotted lines, respectively. The diffracted signals are focused by a second pass through lens **604** and are imaged onto a spectrally-dispersed image plane **608** to illuminate a permanent spectral-plane optical filter **609**, which is patterned so as to selectively reflect, absorb, deflect, or detect, a portion of the spectrally-dispersed multi-wavelength signal.

[0070] In the prior-art SSP filter shown in **Figure 3**, an active device array **307** with electrical controls **309** is positioned in the spectrally-dispersed plane **306**. In sharp contrast, the invention of the present application uses no such active device. The permanent spectral-plane structure **309** has no electrical controls to change

the effect it has upon the multiwavelength optical signal. Instead of changing the filter, the lateral position of the entire dispersed spectrum is adjusted by electrical connections **307** so as to align the desired wavelength signal with the stationary features of the permanent spectral-plane structure.

[0071] With further reference now to **Figure 6**, the lateral position of the dispersed spectrum is controlled by tip/tilt stage **606** to rotate grating **605** to the appropriate angle around its X-axis and Y-axis. Tilt of the collimated beam translates into lateral shift of the dispersed spectra at the dispersed spectral image plane **608**. Regardless of the lateral shift of the dispersed spectrum, light which is reflected by the spectral-plane filter **609** retraces the input path as it is recollimated by a third pass through lens **604**, diffracting again from grating **605**, and is focused back into the input/output fiber **603**. Each wavelength signal beam is diffracted into an angle corresponding to its wavelength; for illustration, two wavelength signals **611** and **612** are drawn using a dashed and dotted lines, respectively.

[0072] The operation of laterally shifting the spectrum is understood with reference to **Figure 7(a) – 7(c)**, which shows the face of input/output fiber **703** such that the central single mode optical fiber core **701** is visible. The dispersed spectral-plane **708** is positioned below the input/output fiber **703** by appropriate initial alignment of the optical system. However, this placement is merely illustrative. The dispersed spectral plane could be placed to the left, the right, or any other orientation to the input/output fiber. Three wavelength signals **702**, **703** and **704** are drawn for illustration, for example corresponding to 1530 nm, 1540 nm, and 1550 nm wavelengths respectively. The three wavelength signals are all emitted from the single mode fiber core **701**, where they overlap.

[0073] With further reference now to **Figure 6**, after making a first pass through the spectral demultiplexing system **600** the three signals are imaged into a column of spots in the spectrally demultiplexed plane **608**, where the relative vertical position of each spot is approximately proportional to signal wavelength.

[0074] The spot size in the horizontal (*x*) direction is typically the mode size in the input fiber times the system magnification. If a single lens is used, the magnification is one. The spot size in the vertical (*y*) direction is the convolution of the mode diameter and the spectral shape of the signal in a single WDM channel. More generally, the intensity profile in the *y*-direction is the convolution of the input spectrum with the transverse fiber mode profile. With continued reference now to Figure 7, the spot separation is given by $fD\Delta\lambda$ where f is the lens **604** focal length, D is the angular dispersion of the grating **605** and $\Delta\lambda$ is the wavelength separation of the WDM channels. For the GFF/VOA-replacement application, it may not be necessary for individual WDM channels to be resolved into non-overlapping spots.

[0075] Turning our attention simultaneously to **Figure 7**, in the initial alignment state of the system shown in **Figure 7(a)**, the column of spots **702a**, **703a** and **704a** is centered in the spectrally demultiplexed plane **708**. The filter **609** of **Figure 6**, has a varied characteristic along line **713** such that signals **702**, **703**, and **704** may couple back into input/output fiber **603** of **Figure 6** with varied amounts of attenuation. For example, the varied characteristic might be the reflectivity of the filter **609** of **Figure 6** or it might a deflection angle resulting from a diffraction grating written onto the filter **609**.

[0076] For simplicity we will assume that the characteristic is specular reflection. A variable reflectivity may be achieved in any of a number of ways. The filter may comprise an absorbent or transparent substrate, such as glass, with a coating of variable reflectivity. The reflective coating may be a metal such as gold or may consist of a single- or multi-layer dielectric. The reflectivity of a metal can be varied by a change in its thickness. Alternatively, the metal may be of one thickness but stippled or patterned in a dot matrix so that the average density of the dots over the imaged monochromatic spot determine the reflectivity at a given wavelength. Alternatively, a reflective substrate (mirror), either metallic or

dielectric, may be coated with a material of variable absorptivity. The diffraction into the 0^{th} order of a one- or two-dimensional phase grating may be varied by modulating either the phase or duty cycle of the features.

[0077] In order to perform gain flattening, the variation in reflectivity along line **713** should preferably be a continuous function corresponding to the inverse of the amplifier gain spectrum. Other functions could be chosen, for example to compensate for wavelength-dependent transmittance of the line **713.** Stimulated Raman scattering is one cause of such wavelength dependence.

[0078] With continued simultaneous reference to Figures 6 and 7, and in particular Figure 7(b), there is shown the result when the reflective grating **605** is rotated about the Y-axis. The spots have the same position relative to each other, but each spot is laterally shifted to new positions **702b**, **703b** and **704b** along line **714**. The result is the selection of a new filter shape as shown in **Figure 8(a) – Figure 8(b)**.

[0079] With reference now to that **Figure 8**, filter shapes represented by lines **a** and **b** of the graph depicted in that **Figure 8** may correspond to the desired GFF shapes for two different optical amplifier gain settings. The system has an excess loss that is the loss still present when the reflectivity of the filter is maximized. Note that filter shapes represented by lines **a** and **b** are both designed to have loss minima equal to the excess loss of the spectral dispersing and recollecting optics. If both filters represented by lines **a** and **b** are GFFs for an EDFA, minimizing the excess loss of each minimizes the amplifier NF for both gain settings.

[0080] Returning now to **Figure 7(b)** and with simultaneous reference to **Figure 6**, there it shows the result when the reflective grating **605** is rotated about the X-axis. The spots have the same position relative to each other, but each spot is vertically shifted to new positions **702c**, **703c** and **704c** along line **713**. The result is a shifting of the center wavelength of the filter as shown in **Figur 8(a) –**

8(c). For the amplifier equalization application, tuning the filter center wavelength is typically not necessary during amplifier operation. Thus, this degree of freedom need not be included in the spectral filter design. However, it may be used to compensate for undesired shifts in the wavelength registration that might occur due to changes in the spectral filter's physical properties as a function of temperature or aging. The device temperature dependence could be compensated for using calibration data in a look-up table. Active monitoring of the spectrum output could also be used to provide feedback.

[0081] The actuations described above may be termed "spectrum steering", as the input spectrum is steered to the required position on the permanent spectral-plane structure, as opposed to changing the filter itself. Therefore this type of filter can be called a spectrum steering filter (SSF).

[0082] Optical circulators increase system cost and insertion loss. A second embodiment of an optical filter **900** having an optical input and output and no circulator is shown in **Figure 9**. With reference now to that **Figure 9**, a multi-wavelength input signal carried on input fiber **901** is collimated by micro-optic lens **902** and then illuminate micro-optic lens **903** off-center from the optical axis so that the input signal is focused at an angle to focal point **904**, which forms the input point for the spectrally dispersive imaging system.

[0083] Input light from focal point **904** is collimated by lens **907** and illuminates planar reflective diffraction grating **908** mounted on tip/tilt stage **909** capable of rotating grating **908** about its X-axis or Y-axis. Each wavelength signal beam is diffracted into an angle corresponding to its wavelength; for illustration, two wavelength signals **913** and **914** are drawn using a dashed and dotted lines, respectively. All signals are focused by a second pass through lens **907** and are imaged onto a permanent spectral-plane structure **911** with patterned reflectivity. The spectral signals are reflected at the dispersed spectral-plane and retrace their path through the optical system to be collected into a single image spot. In filter

900, the image spot is at point **904**. Output signals pass through point **904** at a complementary angle to the input signal and illuminate micro-optic lens **903** off-center from the optical axis so that the emerging collimated signal illuminates output micro-optic lens **905** and is focused into output fiber **906**.

[0084] Alternative versions of the designs shown in **Figure 6** and **Figure 9** are possible and contemplated. In an unfolded geometry, for example, the beam deflected by the grating would pass through a separate lens of potentially different focal length. The filter would then reside in a different image plane. This configuration allows greater degrees of freedom for minimizing aberrations, but is bulkier and requires more components. As is well known to those skilled in the art, 4*f* imaging can also be accomplished with curved reflectors in place of lenses. It is also possible to combine the lens and grating function into a single element using a curved ruled or holographic grating, which provides optical power as well as diffraction.

[0085] Both of the designs shown in **Figure 6** and **Figure 9** incorporate structures that direct light from an input fiber, to the filter in the spectrally demultiplexed plane where it is reflected, and to a separate output fiber. In **Figure 6**, an optical circulator is used. In **Figure 9**, a microlens array is used to transform parallel beams of light entering or exiting parallel fibers into beams that intersect at the demultiplexed plane.

[0086] Another option is to place an optical element such as a roof prism near the demultiplexed plane that changes the relative angle of the input and output beam from parallel to converging as shown in **Figure 10**. Each beam has a virtual image on the demultiplexed plane, and the two virtual images are separated by an amount equal to the fiber separation.

[0087] Other design refinements are possible using a variety of optical design techniques. For example, polarization diversity or polarization averaging may be

included to reduce the polarization-dependent loss of the system. Polarization averaging relies on a birefringent quarter-wave plate positioned between the transform lens and the grating. A system with polarization diversity may readily incorporate an internal circulator with the addition of a few optical elements at the device input such as birefringent polarization walk-off crystals, wave plates, and Faraday rotators. In all designs, the fiber ends and the filter must lie within the imaging system's field-of-view in order to minimize aberrations and associated insertion loss.

[0088] **Figure 11** shows several exemplary means for applying tilt to the reflected multi-wavelength signal. Referring now to **Figure 11(a)**, an illustrative single wavelength input beam **1101** is incident on reflective diffraction grating **1105** is mounted directly on 2-axis tip/tilt mount **1106** used to control the direction of the diffracted output signal **1102**.

[0089] In **Figure 11(b)**, input beam **1101** is reflected from a first-surface mirror **1103** mounted on tip/tilt stage **1106** and to illuminate reflective diffraction grating **1105**, now stationary, such that the diffracted output signal **1102** reflects again from mirror **1103**. As in **Figure 11(a)**, the tip/tilt stage controls the direction of the diffracted output, but in this configuration, and as can be readily appreciated, the output angle is approximately twice as sensitive to tip/tilt stage angle as in **Figure 11(a)**.

[0090] In **Figure 11(c)**, the input signal **1101** is diffracted from stationary reflective diffraction grating **1105** and illuminates first surface mirror **1103** mounted on tip/tilt stage **1106**. Mirror **1103** is oriented so that the reflected signal is incident on reflective diffraction grating **1105** where it diffracts a second time. This configuration provides approximately twice the change in output angle as a function of input wavelength (spectral dispersion) as those configurations shown in **Figure 11(a)** and **Figur 11(b)**.

[0091] In **Figure 11(d)**, input signal **1101** is diffracted in passing through transmissive diffraction grating **1104** then is incident upon first surface mirror **1103** mounted on tip/tilt stage **1106**. The reflected signal is diffracted again by a second pass through transmissive grating **1104** to output **1102**. In configurations shown in **Figures 11(c)** and **11(d)**, where the scanned surface is the second reflective surface, rotation of the tip/tilt stage about the z axis controls lateral position of the imaged dispersed signals **702, 703** and **704** shown in **Figure 7**.

[0092] In each of the systems shown in **Figure 11**, the active moving element can be actuated by any of a number of mechanisms known in the art of optical scanning including, for examples, stepper motor driven screws, piezoelectric direct or screw drive actuators, torsional galvanometric actuators, thermal expansion actuation, and direct manual actuators. Other means known in the art for optical beamsteering include micro-electro-mechanical systems (MEMS) actuators such as the devices used for constructing large port-count optical crossconnects. Such crossconnects typically involve two-dimensional arrays of dozens or hundreds of 2-axis gimbal-mounted beamsteering mirrors, where electro-magnetic or electrostatic actuators control each mirror. In the current invention only a single, relatively large diameter, tilt-mirror is required but the same fabrication and drive techniques are applicable.

[0093] Although all of the system embodiments described so far use reflective optical system geometries based on the reflective beam steering configurations shown in **Figure 11**, it is also possible to construct an optically equivalent system using a transmissive beam steering means. Such means can include, for example, use of rotating prism pairs, liquid crystal beam deflectors and electro-optic beam deflectors.

[0094] All of the systems described so far use angular tilt of the collimated signal beams to introduce a lateral shift at the spectrally dispersed image plane.

The same concepts for optical filtering using a permanent spectral-plane structure can be also implemented using a physical translation of either the input fiber or the permanent spectral-plane structure. A variety of physical translation actuators can be used to control lateral position, including for example threaded screws driven by stepper motors, by direct current motors, by piezo-electric actuators, or driven manually.

[0095] As an example, Figure 12 shows an optical filter **1200** in which, an input signal carried on fiber **1201** passes through optical circulator **1202** to input/output fiber **1203**, then is collimated by lens **1222** and illuminates reflective diffraction grating **1223** that is fixed in-position. Each wavelength signal beam is diffracted into an angle corresponding to its wavelength then focused by a second pass through lens **1222** and imaged onto a permanent spectral-plane structure **1234** that reflects the filtered signal back through the optical system, into input/output fiber **1203**, through optical circulator **1202** into separate output fiber **1206**.

[0096] Instead of using a tip/tilt stage for position control, however, spectral plane structure **1234** is mounted on two-axis translation stage **1231** so that its lateral position can be directly controlled by horizontal (X-axis) and vertical (Y-axis) actuators **1232** and **1233**, respectively.

[0097] In **Figure 12**, the two lateral position actuators shown are manual screws. Actuator **1233** then controls the center wavelength of the transmitted signal, and actuator **1232** controls the wavelength bandwidth of the transmitted signal. Equivalent lateral-shifting embodiments can be constructed for each of the systems described herein.

[0098] The ability to monitor the spectral setting of the filter simplifies its control and obviates the need for external optical spectrum analyzers or optical channel monitors. Several layers of monitoring are desirable. First the tip/tilt actuator

should include sensors that monitor the position of the mirror or grating (whichever the movable element). These sensors can be used to provide feedback to the electronic drive circuit in order to facilitate smooth and rapid tuning and to adjust drive voltages as necessary to maintain a constant filter setting.

[0100] It may be desirable to include optical sensing of the filter setting since the position of the beam on the filter could drift due to temperature changes or aging, even as the grating is held in a constant position. The vertical position of the narrow stripe can be registered using a single-axis position sensitive detector (PSD) **1301** located immediately under the spectral filter shown in **Figure 13**.

[0101] In a PSD, an electrical output responds to the centroid of intensity illuminating the detector. Another mechanism of optical sensing is shown in **Figure 14**. With reference now to that **Figure 14**, there is shown a filter **1402** that is a transparent plate with a partially reflective coating on either its top or bottom surface. A cylindrical defocusing lens **1401** that spreads the transmitted light in the *x* direction follows the filter **1402**. A pair of photodetectors **1404, 1405** follows this lens **1401** in the optical path. The focal length of the lens and the separation between the filter and the lens and the lens and the photodiodes are all chosen so that light is incident on both diodes for all spectral filter settings. Moreover, as the beam incident on the filter is translated from the bottom extreme of its range to the top extreme, the power detected by diode A should increase monotonically while that on B should decrease monotonically. Thus, the *x* position of the beam is uniquely measured by the ratio of the photodiode currents, independent of the input spectrum or power or the filter shape.

[0102] If the partially reflective surface is stippled, as in a half-toned gray-scale image, then the light passing through will diffract. The angles of diffraction will depend on the size and density of the metal dots, which vary across the surface of the filter. Thus, the photodiode currents might become a function of the input spectrum and not a unique measure of filter setting. A modified design

eliminates this potential problem. In this design part of the optical spectrum passes through a non-reflective part of the filter. Thus, it is effectively removed from the optical signal. For example, every EDFA gain stage produces amplified spontaneous emission (ASE) that extends beyond the edges of the WDM spectrum. This light may pass through non-reflective (clear) portions of the filter without any diffraction (**Figure 15**).

[0103] As shown in that **Figure 15**, a shield **1505** blocks the transmitted (and diffracted) WDM signal light from striking photodiodes **1503, 1504**. And while the arrangement shown in that **Figure 15** has the shield **1505** positioned after the lens **1501** in the optical pathway, it could instead be placed before the lens or deposited directly onto the back of a filter substrate **1502**. Alternatively, two or more photodiodes could be sized and positioned so that only ASE strikes them, without the need for a shield.

[0104] If the filter has discrete shapes encoded as stripes across its surface, or if the detector has an additional cover filter of dark stripes across it's surface, then *y* positioning can be determined using only one photodetector. The spectral filter (or photodetector cover filter) has bands of very high or very low transmission or reflectivity between each filter stripe, as shown in **Figure 16**. Movement of the diffracted beam vertically from one filter to another is then registered as nulls or peaks in the detected photocurrent. By counting the power oscillations, the change in filter setting is determined. The beam can be locked onto a filter stripe by dithering the beam position vertically and minimizing or maximizing the detected power (depending on whether the stripes are dark or light).

The invention claimed is: